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DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

BULLETIN 395

RADIOACTIVITY OF THE THERMAL WATERS OF YELLOWSTONE NATIONAL PARK

BY

HERMAN SCHLUNDT

AND

RICHARD B. MOORE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1909

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GROTTO GEYSER.

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RADIOACTIVITY OF THE THERMAL WATERS OF YELLOWSTONE NATIONAL PARK.

By HERMAN SCHLUNDT and RICHARD B. MOORE.

INTRODUCTION.

PURPOSE OF THE REPORT.

During the summer of 1906 we conducted a series of field tests for the United States Geological Survey with the object of determining the radioactive properties of the thermal waters of the Yellowstone National Park. In connection with the field work, samples of deposits formed by the springs, some typical rock specimens, and a number of water residues were obtained. In this bulletin the quantitative data of the investigation are presented in a series of tables. An account of the methods of experiment in both field and laboratory precedes the presentation of results, and a discussion follows. We have indicated a possible application of some of the data to a geologic question—the age of some of the spring deposits; but no systematic attempt has been made to relate the facts of radioactivity to the hydrography of the region or to the geology of the park. Since our experiments were conducted chiefly from the chemist's point of view, we have limited our discussion to pointing out the more important characteristics and relations of the data, and comparing them with data on radioactivity in other regions of hydrothermal activity.

WATERS IN YELLOWSTONE PARK.

The thermal waters of the national park are classified by Arnold Hague under three heads, on the basis of incrustations formed by the springs and chemical analyses of some of the waters made by Gooch and Whitfield:[a] (1) Calcareous waters carrying relatively large quantities of calcium carbonate in solution; (2) siliceous acid waters which usually carry free acid in solution and possess an astringent taste; (3) siliceous alkaline waters. In all, about 4,000 hot springs are found in the park and about a hundred geysers.

[a] Gooch, F. A., and Whitfield, J. E., Analyses of waters of the Yellowstone National Park: Bull. U. S. Geol. Survey No. 47, 1888.

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There is but one important group of calcareous waters in the park, namely, Mammoth Hot Springs, near the northern boundary. In the course of their underground flow these waters pass through Jurassic and Cretaceous limestones and become charged with carbon dioxide and mineral matter, which is deposited as travertine. A series of terraces extend more than a mile up a valley and to a height of 1,300 feet. The springs of this locality differ considerably in temperature, the maximum being 74° C., about 18° under the boiling temperature of water at this altitude.

Acid waters occur in the following localities among those we visited: Norris basin, Shoshone basin, Heart Lake basin, Crater Hills, Tower Falls, Mount Washburn, Mud Volcanoes near Yellowstone River, and Grand Canyon of the Yellowstone.

Alkaline waters predominate in the regions of geyser activity. These waters deposit an incrustation of amorphous silica. Springs of this class were tested at Upper and Lower Geyser basins, Excelsior basin, Shoshone basin, Heart Lake basin, and West Thumb of Yellowstone Lake.

SCOPE OF THE INVESTIGATION.

The field tests extended over a period of two months, during which all the principal basins of thermal activity were visited. The spring waters examined embrace the different types found in the park and include water from a number of cold springs. The aim was to test one or more of each type at each basin visited. Wherever gases were evolved from a spring, these also were tested for their radioactive properties. About eighty quantitative tests were made of waters and forty of gases, besides nearly ninety tests of gases largely of a qualitative nature. In the laboratory some fifty solids, consisting of spring deposits, water residues, and rock samples, were examined quantitatively for the radium content.

GENERAL PLAN OF WORK.

The determinations for radioactivity were all made by the electrical method. Several electroscopes of the C. T. R. Wilson type, as modified in some details by Doctor Boltwood and ourselves for this kind of work, were employed in both field and laboratory tests. The procedure in the field was generally as follows: A qualitative test for radium and thorium emanation was first conducted on the escaping gas from the spring. This was followed by a quantitative determination of the radium emanation present in the gas. Meanwhile a sample of the spring deposit was collected and a sample of water taken. Incidentally the temperature of the water was taken and its reaction toward litmus paper tested. At the field laboratory the quantity of radium emanation in the sample of water collected

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was determined, after which the water was evaporated to dryness. The residue thus obtained and the sample of deposit made by the spring were subsequently examined for their radium content in a chemical laboratory.

ACKNOWLEDGMENTS.

The United States Geological Survey defrayed the greater portion of the expense connected with the field tests of this investigation. The Northern Pacific Railway furnished transportation between St. Paul and Gardiner, Mont. The University of Missouri and Butler College loaned most of the scientific apparatus used in the field tests, and the determinations of radium present in the spring deposits and rock samples were conducted in the chemical laboratories of these institutions. The field work came under the direction of C. W. Hayes and Arnold Hague, of the United States Geological Survey. Doctor Hague also placed at our disposal several specimens of typical rocks, which were used in determining the radium content of rocks. Maj. John Pitcher, U. S. Army, extended numerous facilities that materially aided in the field experiments. Capt. William H. Forsythe, U. S. Army, collected several samples of travertine for us at Mammoth Hot Springs. The noncommissioned officers stationed at the military posts throughout the park assisted in various ways.

APPARATUS.

DESCRIPTION OF ELECTROSCOPES.

Three air-tight electroscopes of the C. T. R. Wilson type were employed in the field and laboratory tests. Two of these we had used in a previous investigation on the radioactivity of waters.[a] These instruments were constructed in the main according to the specifications given by Boltwood.[b] Figure 1 shows one of the electroscopes but does not show the reading microscope for observing the fall of the leaf. The instrument consists of a rectangular brass frame 15 by 10 by 6 centimeters, fitted on the front and back with pieces of plate glass. On the top, the frame carries a short piece of wide glass tubing (T) surmounted by a threaded brass ring (R), into which a removable brass cap (C) screws. A short piece of glass tubing passes through a hole in the cap and a brass rod (*r*) is cemented in the glass tube by means of sulphur or wax. The lower end of the brass rod extends into a rod of sulphur, which serves as the insulating material to support the leaf system. The plate (*p*) to which the leaf is fastened is embedded for a short distance in the other end of the sulphur rod. A special feature of the electroscope is the device

[a] Jour. Phys. Chem., vol. 9, 1905, p. 321.
[b] Am. Jour. Sci., 4th ser., vol. 18, 1904, p. 97.

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for charging it.[a] A piece of soft iron wire (*w*) is suspended from a hook on the brass rod (*r*) which projects out through the screw cap. The wire extends just below the sulphur insulator and terminates in a right-angle bend. In its normal position the wire does not touch the plate carrying the leaf, but by bringing a magnet near the wire,

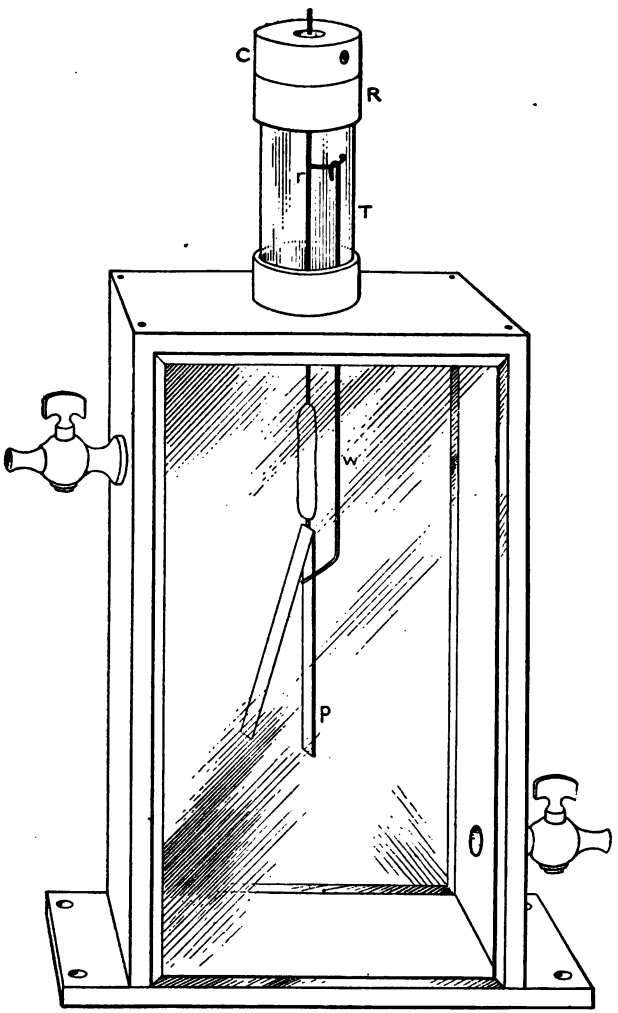

FIGURE 1.—Electroscope.

it can be deflected so as to make metallic contact between the rod (*r*) and the plate (*p*). All of the brass joints are soldered and the other joints are made air-tight by means of hot wax, except that between the brass ring and cap, where a rubber washer excludes the air. The electroscope is provided with two good brass stopcocks.

[a] The same device was used by Strutt, Phil. Mag., 6th ser., vol. 5, 1903, p. 680; and by Boltwood, loc. cit.

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Aluminum leaf was used in the instruments. It was readily and firmly fastened to the carrying blade by moistening the upper portion of the blade and then pressing it firmly against the leaf. The sulphur rod and the aluminum leaf successfully withstood the transportation by rail and in the field. In two of the electroscopes the original leaf served throughout the entire series of field experiments. The volume of the electroscopes was, respectively, 490, 590, and 600 cubic centimeters. A rod of vulcanite about 20 centimeters long was used for charging. After metallic connection between the leaf system and the projecting rod had been made, the charged vulcanite was touched to the brass rod, and by gentle rubbing, the desired potential on the leaf system was produced. After withdrawing the vulcanite the rod and cap were earthed for an instant.

Each electroscope was fastened securely to a wooden base. The fall of the leaf was observed by means of a microscope firmly supported by a brass holder which was likewise screwed to the wooden base. The glass scale in the eyepiece was divided into ten divisions and each of these was again divided into tenths. The diameter of the field corresponding to the hundred small divisions of the scale was approximately 5.2 millimeters for each of the microscopes. The rate of fall of the leaf was generally obtained by noting the time required for the leaf to fall 60 small divisions between the same two points of the scale. The time interval was measured by means of a stop watch recording fifths of a second. To secure uniform and ready adjustment of the instruments for the field tests a circular level was attached to the base. Suitable carrying cases were constructed for the electroscopes to facilitate their safe transportation in conducting the outdoor experiments.

STANDARDIZING THE ELECTROSCOPES.

To make quantitative activity measurements by means of electroscopes, each instrument must be standardized. The method of standardizing employed was the one first proposed by Boltwood,[a] which we had adopted in our earlier electroscopic determinations of radium emanation in waters.[b] Strutt has followed a similar procedure in his extensive investigations on the radium content of rocks and spring deposits.[c] The method is based upon the well-established fact that the radium present in natural uranium minerals stands in constant ratio to the uranium. Rutherford and Boltwood[d] have recently redetermined this ratio and found that one gram uranium is in radioactive equilibrium with 3.8×10^{-7} grams radium. If then the emanation from a small weighed quantity of a uranium mineral,

[a] Am. Jour. Sci., 4th ser., vol. 18, 1904, p. 381.
[b] Jour. Phys. Chem., vol. 9, 1905, p. 320; Trans. Am. Electrochem. Soc., vol. 8, 1905, p. 291.
[c] Proc. Roy. Soc., vol. 77, 1906, p. 472.
[d] Am. Jour. Sci., 4th ser., vol. 22, 1906, p. 1.

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whose percentage of uranium is known from a chemical analysis, be introduced into the electroscope, and the rate of fall of the leaf noted, the data are at hand from which a constant for the electroscope may be calculated that shall express the uranium (or radium) required to produced a fall of the leaf one division in unit time.

The operation of standardizing was carried out as follows: The apparatus used for separating and collecting the emanation is shown in figure 2. A small quantity of a standard sample of powdered uraninite containing 68.9 per cent uranium was weighed out and put in the flask (F), of about 50 cubic centimeters capacity. Generally 15.7 milligrams of uraninite was used, as the emanation separated from this quantity of the mineral upon solution represents the total emanation associated with 10 milligrams uranium. A rubber stopper fitted with a small dropping funnel and a short delivery tube was then inserted in the flask and connections were made with the gas burette (B), which had previously been filled with freshly boiled distilled water, to which a few cubic centimeters of sodium hydroxide had been added. A few cubic centimeters of diluted nitric acid was then poured into the drop funnel; the leveling reservoir of the gas burette was lowered below the level of the acid in the funnel; and then by opening the pinchcock (*c*) and the stopcock of the funnel most of the acid was allowed to flow into the flask. The stopcock was then closed, the leveling reservoir replaced, and the flask gently heated until the uraninite had dissolved. When any gas collected in the stem of the funnel during this operation it was displaced by water introduced through the funnel. By withdrawing the flame for a moment sufficient water was allowed to flow into the flask to continue the boiling for ten minutes. The gas collected in the burette, after standing for ten

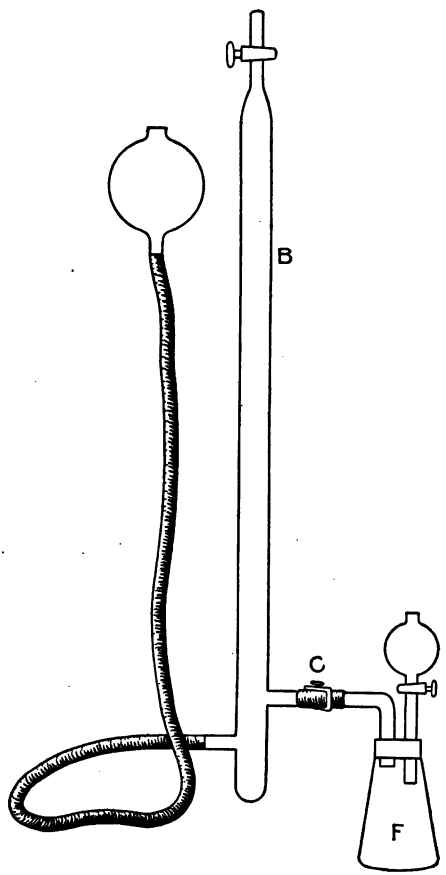

FIGURE 2.—Apparatus for separating emanation from uraninite.

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minutes, was then introduced into the electroscope, which had previously been partly exhausted, to be standardized. After three hours, the time in which the activity attains a maximum, the rate of leak was determined.

The standardizing record of one of the electroscopes, which is designated in our journal as No. 1, is given below in Table 1. The quantity of uraninite used in each experiment was 15.7 milligrams. Determinations numbered 3 and 4 were conducted in Yellowstone Park in the field laboratory, and the others were made in the chemical laboratory of the University of Missouri. The samples of uraninite used for standardizing in the park were carefully weighed out and sealed in small glass tubes before we started for the field work. The first column in the table gives the number of the experiment; the second, the date on which it was conducted; the third, the number of scale divisions the leaf fell per minute at the time of maximum activity—three to three and one-half hours after the introduction of the gas. The normal air leak of the electroscope, 0.15 division per minute, has been deducted from the readings. The last column gives the constants computed for the electroscope. These values represent the quantity of uranium that would cause a fall of the leaf of one scale division per minute, if all of the emanation produced remained in the sample. In this particular sample of uraninite, 7.6 per cent of the emanation is continuously lost at room temperatures. The quantity of uraninite used in the experiments, however, 15.7 milligrams, contains the maximum quantity of emanation that would be found associated with 10 milligrams of uranium. The sample taken contains 10.8 milligrams of uranium. Hence the quantity of uranium responsible for a leak of one division per minute if all the emanation produced were retained is obtained by dividing 10 milligrams by the observed leak per minute.

TABLE 1.—*Standardizing record of electroscope No. 1.*

Number.	Date.	Observed leak (divisions per minute).	Uranium per division per minute (grams $\times 10^{-4}$).
1	June 28, 1905	44.1	2.27
2	Aug. 15, 1905	45.0	2.22
3	July 19, 1906	35.5	2.88
4	Aug. 24, 1906	37.0	2.70
5	Nov. 14, 1906	48.0	2.07
6	Mar. 8, 1907	42.8	2.35
7	May 22, 1907	45.7	2.18

The table shows that the constants obtained in the park are approximately 25 per cent higher than the average of the values obtained at Columbia, Mo. The lower density of the air at the higher altitude is

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an important cause of this difference. The value 2.8×10^{-4} was used for this electroscope in converting scale readings taken in the field to the uranium standard. The radium constant of the electroscope during the field tests was the product of 2.8×10^{-4} and 3.8×10^{-7}, or 10.64×10^{-11}.

In the field the constant for electroscope No. 2 was found to be 7.7×10^{-4} grams uranium and for electroscope No. 3 the value was 1.52×10^{-4} grams uranium for a leak of one scale division per minute.

ELECTRIC CAPACITY.

Inasmuch as some investigators, chiefly those on the continent of Europe, have expressed their quantitative results for the radioactivity of water and gas samples in electrostatic units, we have standardized two of our electroscopes in C. G. S. units. We are thereby enabled to express our values in absolute units and to compare the activities obtained with those given for some of the well-known thermal waters of foreign countries.

In expressing the radioactivity of waters, the standards proposed by Curie and Laborde[a] and by Mache[b] have been generally adopted. The activity is the value obtained in electrostatic units for the saturation current produced by the radium emanation present per liter of water. For gases the saturation current produced by a liter of the gas is given as its radioactive value. Mache, in expressing the value of activities, deducted from the observed values the current due to the disintegration products of the radium emanation. The values given by Curie and Laborde represent approximately the total maximum activity, which includes the activity of the disintegration products of the emanation.

To express the saturation current in electrostatic units two quantities must be determined—(1) the rate of fall of the leaf in volts per unit of time and (2) the electric capacity of the leaf system. In making our electroscopic readings we found the number of divisions the leaf fell per minute. To convert these readings into volts it is only necessary to calibrate the scale in the eyepiece of the reading microscope between the two points for which readings were generally made. This operation was conducted as follows: The glass plate on the back of the electroscope was replaced by one of cardboard, which was provided with an opening about 1.5 centimeters square, opposite the point where the leaf is attached to the carrying blade. The leaf system was then connected through the opening in the cardboard to one pole of a set of small storage batteries and the case of the electroscope to the other pole. The positions of the leaf corresponding to several voltages between 300 and 400 were then noted. In this way it was

[a] Compt. Rend., vol. 138, p. 1150.

[b] Sitzungsber. K. Akad. Wiss., Wien, Math.-nat. Klasse, Abt. 2a, vol. 113, pp. 1329–1352.

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found that one small division of the scale of electroscope No. 1 represented 1.24 volts, and for electroscope No. 2 one division represented 2.80 volts. The electric capacity of the electroscopes was determined by means of a Harms standard condenser whose capacity was 42.5 centimeters. The procedure given by Harms[a] was carefully followed. Connections with the leaf system were again made through the opening in the cardboard. The capacities of the instruments were small; that of electroscope No. 1 was found to be 2.81 centimeters and that of No. 2, 3.51 centimeters. The leaf system of electroscope No. 1 had the following dimensions: The aluminum leaf was 1.0 centimeter wide and 5.4 centimeters long, and it was fastened to a blade 0.9 centimeter wide and 6.2 centimeters long.

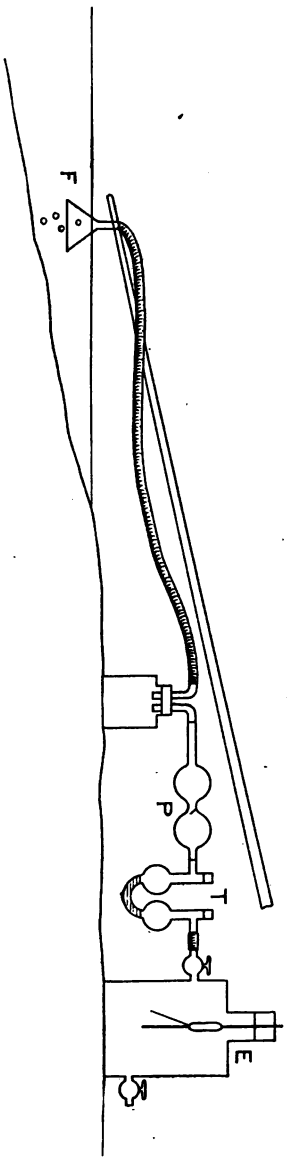

FIGURE 3.—Apparatus for qualitative tests in the field.

METHODS OF PROCEDURE.

FIELD EXAMINATION OF GASES.

From many of the springs in the park gases escape with the issuing water. In some instances the evolution of gas from the hot water is so copious as to give the appearance of boiling. It is also not uncommon to see gases bubbling up in considerable quantity at certain points in the pools of hot water that dot the sinter plain in most of the different basins of thermal activity. Systematic tests were conducted with the escaping gases throughout the series of field experiments. The gas activity was generally the first determination made. It was conducted at the spring and consisted of two parts: (1) A qualitative test for the detection of thorium emanation as well as radium emanation; (2) a quantitative determination of the radium emanation present in the gas.

The principal parts of the apparatus used in the qualitative test are shown in figure 3: A glass collecting funnel (F) 12 centimeters in diam-

[a] Phys. Zeitschrift, vol. 5, pp. 49–50.

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eter, a rubber hand bellows (P), a drying tube (T) containing strong sulphuric acid, and one of the electroscopes (E) were connected in series by rubber tubing. By operating the hand bellows the water gas collecting in the funnel was gradually made to displace most of the original air in the electroscope. One to five minutes was generally required for this operation, the time depending upon the rate at which the gas collected in the funnel. When 1 to 2 liters of gas had been passed along the circuit, the pumping was stopped and the cocks of the electroscope closed. The leaf was then quickly charged and readings taken on its rate of fall by means of a stop watch and

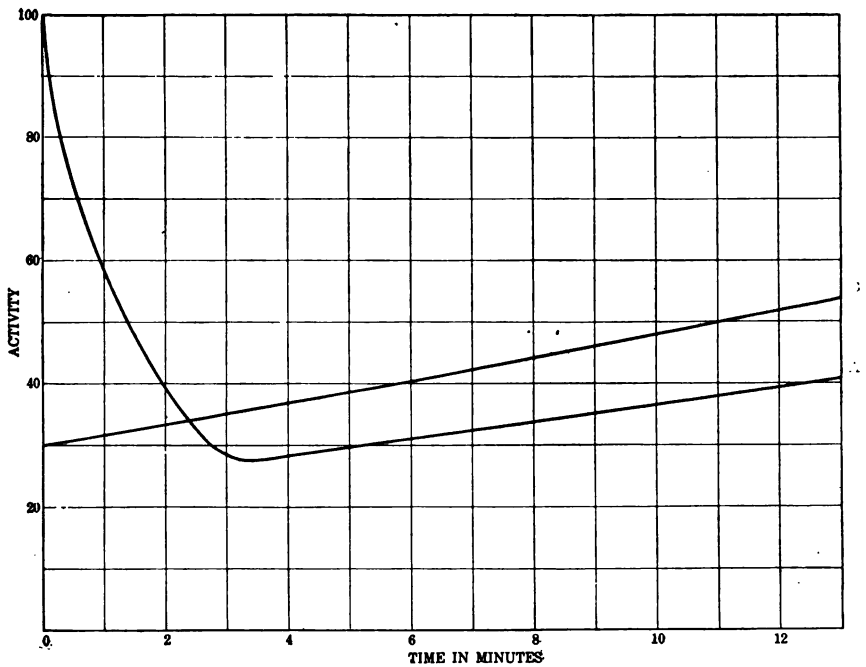

FIGURE 4.—Curves showing difference in the radioactivity of gases containing (A) thorium and radium emanation and (B) radium emanation.

the reading microscope. By taking readings at suitable intervals for five to ten minutes the presence of thorium as well as radium emanation could be detected. Sometimes the leaf was charged before the transfer of gas through the electroscope was interrupted, so that readings could be taken at the instant the leaf appeared in the field of the microscope. By the latter procedure the relative activities of the thorium and radium emanation in the electroscope may be more readily obtained.

In figure 4 the points for curve A represent a series of readings obtained with a gas containing both thorium and radium emanation, and

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curve B represents the data for a gas containing only radium emanation. The activity is given in an arbitrary scale for the time in minutes. In the gas containing both emanations the activity drops very rapidly at first, falling to approximately half value in a minute—the characteristic rate of decay of thorium emanation. The activity remaining after five minutes mainly represents that of the radium emanation, showing its characteristic initial rise, as in curve B. After readings had been taken for ten minutes the gas in the electroscope was blown out with the hand bellows to avoid the accumulation of the disintegration products of the emanation. After half an hour the instrument was generally ready for another test.

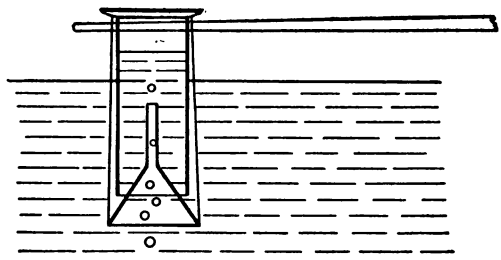

FIGURE 5.—Apparatus for collecting gas in the field.

If the escaping gas was found to be active, a known volume was collected over water and this was introduced into an electroscope, which had previously been partially exhausted, for a quantitative determination of the radium emanation. The device generally employed for collecting the gas is shown in figure 5. A collecting funnel and a graduated cylinder attached to a pole were filled with water and then inverted over the escaping gas. When 50 to 100 cubic centimeters of gas had collected in the cylinder, it was brought within arm's reach, the funnel removed under water, the cylinder transferred to a small pneumatic trough, and the whole removed from the pool to cool. To hasten the cooling, the trough was oftentimes placed in a larger vessel of cold water. After ten minutes the temperature of the water was taken and the volume of the gas read. In the meantime a rubber tube supplied with a pinchcock was introduced up the cylinder, as shown in figure 6. The gas was then transferred to the partially exhausted electroscope with the drying train in circuit. The water gas remaining in the train and tubing was swept into the electroscope by admitting outside air until atmospheric pressure was restored. The rate of fall of the leaf was then taken at intervals during several hours following. The maximum activity, reached about three hours after the introduction of the gas, was made the basis of calculations

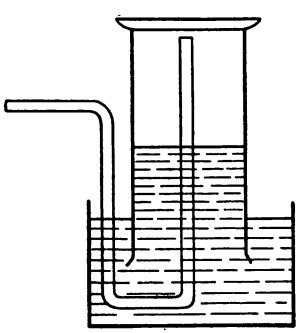

FIGURE 6.—Detail of apparatus for collecting gas in the field.

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in these measurements. Figure 7 represents the results obtained in one of these determinations. After four hours (point B on the curve) the gas was blown out. The rapid rate of decay of the induced activity, as well as the initial rise, are characteristic of radium emanation.

FIELD TESTS OF WATERS.

In almost all the tests the determination of the activity of the water samples consisted in a quantitative measurement of the radium emanation in a fresh sample of water. The emanation dissolved in a known volume of water was separated by boiling in a form of apparatus which had been used in earlier investigations on the radioactivity of

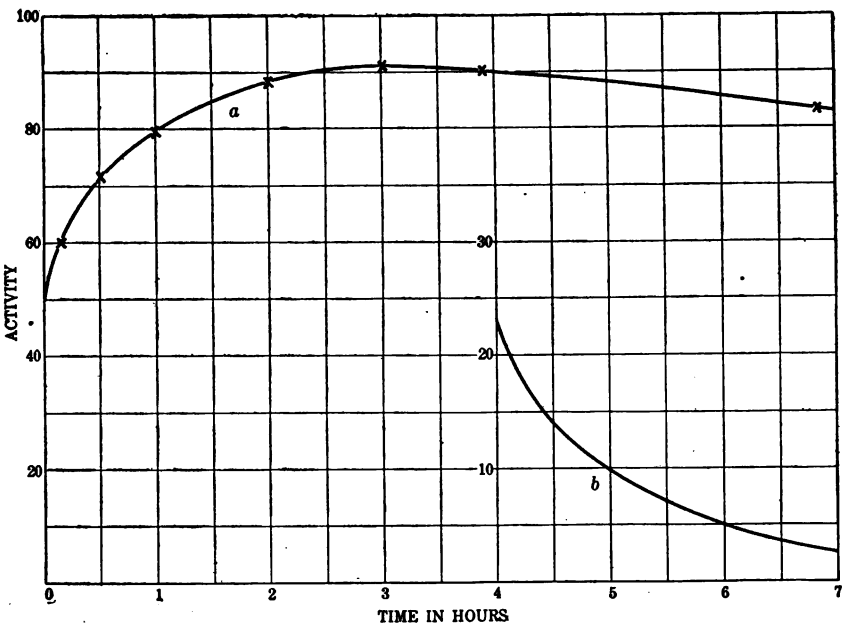

FIGURE 7.—Decay curve of radium emanation.

waters. The apparatus is figured and fully described in the Journal of Physical Chemistry, volume 9, pp. 324–326. Several parts of the apparatus were modified to adapt it to field conditions. Metal vessels were substituted for the glass ones formerly used as leveling reservoirs. The gas burette for measuring the volumes of the separated gases was rarely used. The heating was done with a small wood fire. The boilers used were provided with bails and also served as collecting vessels. A small quantity of caustic soda was generally added to the water sample before boiling to fix the carbon dioxide carried by the waters.

About ten minutes after boiling had ceased the separated gas was drawn into one of the standardized electroscopes, which had pre-

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viously been partially exhausted by means of a hand suction pump. The activity was then ascertained in the usual way by noting the rate of fall of the charged leaf at intervals of fifteen to thirty minutes for several hours. The maximum leak, obtained three and one-half hours after the introduction of the gas, was made the basis for calculating the activity of the water sample.

The presence of radium emanation in a natural water does not necessarily indicate the presence of dissolved radium salts. Being a gas, the emanation found in a water sample may simply have diffused into it in the course of its underground flow. Such a water, however, has only temporary activity, for the emanation when separated from its parent radium decays rapidly, falling to half value in about four days, one-fourth value in eight days, and so on, until at the end of a month the activity has practically disappeared. If radium salts are present the water sample will still be radioactive after standing in a sealed vessel for a month and the residue after evaporation will also be radioactive. The presence of radium salts may be established by either of two methods—(1) by an examination of the residue obtained by evaporation, or (2) by storing the sample from which the emanation has been expelled by boiling, and at the end of a week or two again determining the emanation that has accumulated. As our facilities for storing waters were limited we evaporated the samples and reserved the residues for examination in the laboratory after our return from the park. The water was evaporated on a camp stove in iron bowls of about 2 liters capacity. The greater portion of the residue was removed with a spatula and the firmly adhering portion was removed by vigorous scouring with emery cloth, a fresh piece of cloth being used for each residue.

TESTING OF SOLIDS.

In determining the radium content of the spring deposits, water residues, and rock samples the method devised by Strutt [a] in his investigations on the distribution of radium in the crust of the earth was followed in the main.

The calcareous deposits were dissolved in hydrochloric acid and the solution stored for several weeks in tightly corked flasks. The weights of material used in these determinations are given in the tabulated statement of results which appears further on. The slight quantities of insoluble residue were not removed, but were stored with the solutions. After the requisite period of storage the accumulated emanation was boiled off in an apparatus similar to the one used in the tests with water samples, except that the flask in which the solution was stored served as the boiler. The quantity of ema-

[a] Proc. Roy. Soc., vol. 77, 1906, p. 472.

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nation was then determined, as it was for water and gas samples, by means of a standardized electroscope. With the siliceous deposits and the rock samples the determination of radium in small quantities involves more labor. The sample must first be ground to go through a 100-mesh sieve. Then it is fused with a mixture of alkali carbonates, the mass extracted with water, and the soluble portion stored in a tightly corked flask. The residue after it is dissolved in hydrochloric acid is stored in another flask. The activity of the two solutions is determined at the end of three or four weeks, as before described in connection with the water tests. From the data thus obtained the quantity of radium per gram of substance is readily calculated.

RESULTS OF THE EXPERIMENTS.

GENERAL STATEMENT.

The experimental results of this investigation are presented in five tables, showing the radioactivity of gases, waters, water residues, spring deposits, and rock samples. Finally, the results for the activity of gases, waters, and deposits are summarized for better comparison in an additional table.

EXAMPLE SHOWING METHOD.

The data obtained in the test of White Sulphur Spring at the Lower Geyser basin are summarized here to illustrate the procedure followed and to show the method of calculation of the values given for radioactivity in the tables. The test was conducted August 1, 1906. The temperature of the water in the pool at the point where samples were collected was 59° C., and the water was slightly alkaline to litmus paper. The gas escaping from two orifices under the water at the south end of the pool were first tested qualitatively for thorium and radium emanation by the use of the apparatus shown in figure 3. As the gas issued relatively slowly, ten minutes was consumed in passing the accumulating gases along the circuit through electroscope No. 1. About 1,100 cubic centimeters of gas was transmitted, as measured by 15 squeezes of the hand bellows. The first readings of the fall of the charged leaf were taken thirty seconds after the gas delivery was stopped. In this case no decrease in activity was observed during the first two minutes of observation. Hence thorium emanation was absent. In the course of ten minutes the leak increased about 12 per cent, which is characteristic of radium emanation. The gas evidently was relatively rich in emanation, as the leak was fully 1,000 times the usual air leak of the instrument. Our field journal shows that 60 small divisions of the scale were passed over by the leaf in eleven and six-tenths seconds. After twelve minutes of observation the gas was blown out and the electroscope set aside for a time to wait for the

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NORRIS GEYSER BASIN.

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decay of the induced activity. Later in the day a quantitative determination of the radium emanation present in the escaping gas was made with the same electroscope. Ninety cubic centimeters of gas were collected over water (temperature 40° C.) and introduced into the partially exhausted electroscope. At maximum activity the leaf fell 23.6 small scale divisions per minute after deducting the normal air leak, which was 0.2 division per minute. The volume of the gas sample reduced to normal temperature and pressure is 56.3 cubic centimeters.[a] In this electroscope a leak of one division per minute represented 2.8×10^{-4} grams uranium or 10.64×10^{-11} grams radium. The activity of the gas per liter, in terms of the uranium standard, is hence expressed by the following equation:

$$\frac{23.6\times2.8\times10^{-4}\times1,000}{56.3}=117\times10^{-3}.$$

Expressed in terms of the radium standard the activity equals $117\times10^{-3}\times3.8\times10^{-7}=44.5\times10^{-9}$.

The value of the ionization current per liter of gas, in electrostatic units, is obtained by substituting in the formula:

$$i=\frac{q\times c\times1,000}{300\times t\times56.3}.$$

For q may be put the potential fall in volts during the interval of time (t) expressed in seconds, and c is the electric capacity of the electroscope. Since each division of the scale represents 1.24 volts, and the capacity is 2.81 centimeters, the numerical equation for the value of the ionization current is:

$$\frac{23.6\times1.24\times2.81\times1,000}{300\times60\times56.3}=81.2\times10^{-3}\text{ electrostatic units.}$$

For the determination of the activity of the water from this spring, the water gas separated from a sample of 2,570 cubic centimeters was introduced into electroscope No. 2. This sample of water was collected in the immediate vicinity of the orifices from which the gas issued. The maximum net leak observed was 10.9 scale divisions per minute. The activity of the water sample, per liter, in terms of the uranium standard, is given by the equation:

$$\frac{10.9\times7.7\times10^{-4}}{2.57}=32.6\times10^{-4}.$$

This value is equivalent to $1,238\times10^{-12}$ grams radium. The numerical equation for the ionization current in electrostatic units has the form:

$$\frac{10.9\times2.80\times3.51}{300\times60\times2.57}=2.33\times10^{-3}.$$

[a] In reducing the observed gas volumes to those for normal conditions the value 600 millimeters was used for the barometric pressure in all the calculations. Correction was of course made for the aqueous tension.

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The water sample upon evaporation left a residue weighing less than 2 grams. Its radium content was too small to be determined in so small a quantity of material. It therefore follows that the activity of the water is temporary in nature, and that the dissolved radium emanation did not come directly from the radium salts carried in solution. The greater portion of the emanation doubtless diffused into the water from the radium-bearing rocks with which the water came in contact in the course of its underground flow.

RADIOACTIVITY OF GASES.

The names of the gas sources in Table 2 are those found in the atlas accompanying Monograph 32 of the United States Geological Survey, entitled "Geology of Yellowstone Park." The locality names in the second column of the table are also the official names. Names inclosed in quotation marks are not official. The third column shows whether thorium emanation was detected in the qualitative field test. In some instances the activity due to thorium is compared with that observed for radium. In the last column the activity values are recorded in both the uranium and the radium standards. They represent the radium emanation present per liter of gas. The blank spaces indicate that no test was conducted.

TABLE 2.—*Radioactivity of gases in Yellowstone Park.*

MAMMOTH HOT SPRINGS.

Name of source.	Location.	Thorium emanation.	Radium emanation.	
			Uranium (grams $\times 10^{-3}$).	Radium (grams $\times 10^{-9}$).
Soda Springs	Summit Lake		1.5	0.57
Squirrel Springs	Highland terrace	None.	7.5	2.85
Orange Spring	....do	None.	Trace.	.....
Bath Lake	....do	None.	Trace.	.....
Main Spring	Main terrace	None.	None.	.....
Blue Spring	....do	None.	None.	.....
Cleopatra Spring	....do	None.	None.	.....
Hymen Spring	Hymen terrace	None.	None.	.....

NORRIS GEYSER BASIN.

"Black Sulphur" Spring	400 feet west of hotel	None.	>39.6	15.0
Opal Spring	Porcelain basin	None.	>18.0	6.8
Locomotive	Near Congress Geyser	7.5×Ra.	>52	19.8
Sky Rocket Geyser	Porcelain basin	Present.	Present.	
Pool	Near Sky Rocket Geyser	(?)	Present.	
Primrose Spring (1)	.....	2×Ra.	>13	4.9
Primrose Spring (2)	.....	Trace.	> 9	3.4
Paint Pot	Near Locomotive	Present.	Present.	
Orpiment Pool	.....	.....	67.7	25.7

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TABLE 2.—*Radioactivity of gases in Yellowstone Park*—Continued.

Name of source.	Location.	Thorium emanation.	Radium emanation.	
			Uranium (grams $\times 10^{-3}$).	Radium (grams $\times 10^{-9}$).
LOWER GEYSER BASIN AND TERRACE SPRINGS.				
Terrace Spring (1)[a]	Gibbon River	None.	> 6	2.3
Terrace Spring (2)[a]	do	15×Ra.	> 13	4.9
Terrace Spring (3)[a]	do	3×Ra.	> 11	4.1
Pool	Near and northwest of Clepsytra Geyser.	None.	1,200	456
Fountain Geyser	Firehole Geyser basin	None.	None.	
Vapor vent	Near Fountain Geyser	None.	Trace.	
Clepsytra Geyser	Firehole Geyser basin	None.	Trace.	
Jelly Spring	do	Trace.	40.7	15.5
White Sulphur Spring (1)	do	None.	117	44.5
White Sulphur Spring (2)	do	None.	69	26.2
Mammoth Paint Pots (1)[b]	do	None.	None.	
Mammoth Paint Pots (2)[b]	do	Trace.	Trace.	
Mammoth Paint Pots (3)[b]	do	(?)	Trace.	
Firehole Lake (1)	East side of lake	None.	864	329
Firehole Lake (2)	West side of lake	None.	478	182
Great Fountain Geyser		None.	Trace.	
Mushroom Pool	Firehole basin	None.	756	287
Pool east of road	Excelsior basin	None.	492	187
UPPER GEYSER BASIN.				
Cauliflower Pool	Biscuit basin	None.	122	46.3
Jewell Geyser	do	Trace.	Yes.	
Spring and pool	North of Gem Geyser	None.	843	321
Bench Spring		None.	366	139
Grotto Geyser		None.	None.	
Splendid Geyser		None.	None.	
Punchbowl		None.	Trace.	
Giant Geyser		None.	None.	
Pool near Economic Geyser	Grand Group	None.	508	193
Turban Geyser	do	None.	Trace.	
Pool	Across road from Castle Geyser.	None.	514	196
Giantess Geyser	Geyser Hill	None.	Trace.	
Pool near Model Geyser	do	None.	1,218	462
Beehive Geyser	do	None.	None.	
Old Faithful Geyser		None.	Present.	
Pool, east of Spouter	Emerald group	None.	206	78
Pool, near Emerald Pool	do	None.	509	194
"Handkerchief" Pool	do	None.	416	158
Lone Star Geyser	Lone Star basin	None.	None.	
Pool on hillside	do	None.	416	158
SHOSHONE GEYSER BASIN.				
Wave Spring		None.	>750	285
Three Crater Spring		None.	861	328
Union Geyser, north cone		None.	>600	228
Union Geyser, middle cone		None.	Trace.	
A sulphur spring		None.	896	340
Steam vent	Near sulphur spring	None.	> 30	11
Taurus Geyser		None.	> 50	19
HEART LAKE, GEYSER BASIN.				
A hillside spring	South of Rustic Geyser	None.	>700	266
Pool east of stream	Factory Hill	None.	939	356
A boiling pool west of stream	Heart Crater, Factory Hill	None.	59	19
"Orange" Pool	Head of basin	2×Ra.	243	92

[a] Terrace Spring No. 1 is the lowest one on the terraces. It discharges large quantities of gas; No. 3 is on the third terrace; the volume of gas discharged from Nos. 2 and 3 is relatively small; less gas escapes from No. 2 than No. 3.

[b] Test 1 on the west side of the group; No. 2 on the south side, and No. 3 on the east side.

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TABLE 2.—*Radioactivity of gases in Yellowstone Park*—Continued.

WEST THUMB, YELLOWSTONE LAKE.

Name of source.	Location.	Thorium emanation.	Radium emanaton.	
			Uranium (grams $\times 10^{-3}$).	Radium (grams $\times 10^{-9}$).
Pool west of road	One mile from military post.	None.	382	145
Pool east of road	do	None.	45	17
Yellowstone Lake	Boat pier	None.	266	107
Paint Pot	Near lunch station	Present.	>150	51
Pool near Paint Pot	Lunch station	Equal to Ra.	309	117
Fish Cone		None.	123	47

LOCALITIES ALONG YELLOWSTONE RIVER.

Pool	South area of activity, mud geysers.	None.	49	18.6
Pool	East of large mud geyser	None.	155	59
Yellowstone River	East of Camp Howard	None.	7.6	2.9
Steam and gas vent	Mud geysers	None.	Trace.	
Hellbroth Springs	Mount Washburn	4×Ra.	>110	42
Devil's Ink Pot	do	Present.	> 40	15
Black Pool (1)	West side of formation, Mount Washburn.	Present.	> 50	19
Black Pool (2)	Mount Washburn	(?)	17.2	6.5
Nymph Spring	Tower Falls	(?)	19.2	7.3

RADIOACTIVITY OF WATERS.

The values recorded for the activities of the water samples in Table 3 are expressed in terms of both the uranium and the radium standards. They represent the radium emanation in a fresh sample of water. In several instances some time elapsed between the collection of the sample and the determination. In such tests correction was made for the decay in the activity of the samples during the interval between the time of collecting and the time of testing by means of the formula $I_o = I_t e^{-rt}$, expressing the decay of activity with the time. I_o represents the initial activity, I_t the activity observed t hours after the water was collected, and r the radioactive constant of radium emanation. The value of r used in the calculations was 0.0077, which is an approximate mean of the values found by several investigators. The temperatures given were taken with a normal centigrade thermometer graduated in degrees. The instrument was not self-registering. At some of the springs it was difficult to get accurate readings, as the hot water and vapors interfered materially with readings at close range. For the most part the values recorded are correct to within half a degree. As the reaction of the waters to litmus paper was tested, the results are recorded in a separate column. This table, like the preceding one, is subdivided on the basis of the more important localities. Several of the names recorded are not found on the maps of the United States Geological Survey. Most of

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these, however, are probably the official names, as they appear on the printed signboards. New names are inclosed with quotation marks. We aimed to include the spring waters of the park analyzed by Gooch and Whitfield.[a]

TABLE 3.—*Radioactivity of waters in Yellowstone Park.*

MAMMOTH HOT SPRINGS.

Name of source.	Location.	Temperature.	Reaction, etc.	Activity.	
				$g \times 10^{-14}$ U.	$g \times 10^{-11}$ Ra.
		°C.			
Flume water	Near buffalo corral	11		None.	
Hot River (1a)[b]	1 mile north of fort	51	Alkaline	42.3	161
Hot River (1b)[b]	do	51	do	37.9	144
Hot River (2)[b]	do		do	29.3	111
Hymen Spring	Hymen terrace	71	do	Trace. (?)	
Cleopatra Spring	Foot of Minerva terrace	71	do	None.	
Diana Spring	Minerva terrace	70.5	do	None.	
Naiad Spring	Foot of Main terrace		do	None.	
Blue Spring	Main terrace	70	do	None.	
Main Spring	do	71	do	None.	
"New Blue Spring"	do	70	do	None.	
Squirrel Spring	Highland terrace	32	do	1.85	7
Bath Lake	do	46		Trace. (?)	
Dedolph Spring	do	39	Alkaline	5.27	20
Orange Spring	do	63.5	do	None.	
Cold Spring	½ mile south of fort on old road to Golden Gate.	10.5	do	7.3	27.7
Soda Spring	Summit Lake	15.5	Acid	3.2	12.2
Apollinaris Spring	10 miles south of Mammoth Hot Springs.	9.2	Slightly acid	31.9	121

NORRIS GEYSER BASIN.

"Circular" Springs	5 miles north of Norris	85	Neutral	0.34	1.3
"Iron" Spring	Solfatara Creek	15	Faintly alkaline	13.1	49.7
A thermal spring	Near Iron Spring and 1 mile north of post on trail.	50.5	Neutral	1.9	77.2
A cold spring	1 mile east of Norris on road to canyon.	16		17.5	66.5
Gibbon River				None.	
A hot spring	1 mile up Gibbon River	75	Neutral	33.5	128
A carbonated spring	In meadow across river from army post.			20.0	76
An iron spring	do			18.7	71
Realgar Spring	100-spring plain			10.6	40.5
The reservoir	do	71	Slightly acid	6.9	26.5
"Black Sulphur" Spring	300 feet west of hotel	90		4.6	17.4
Opal Spring	Porcelain basin	58	Slightly acid	1.1	4.2
An alum spring	do	67	Strongly acid	1.23	4.6
Pool near Constant Geyser	do	51	Slightly acid	7.0	26.6
Congress Geyser		89	do	1.15	4.4
Locomotive		82	Strongly acid	1.2	4.55
Primrose Spring	Near Nuphar Lake	88		1.0	3.8
"Drab" Spring	Near Primrose Spring	89	Strongly acid	0.5	1.9
A cold spring	6½ miles south of Norris, by roadside.			2.05	7.8
A carbonated spring	8 miles south of Norris, by roadside.	(c)		9.0	34

[a] Bull. U. S. Geol. Survey No. 47. 1888.

[b] Samples 1a and 1b were collected where the main current of Hot River first issues from the rock. Test 1a was made July 15, 1906; 1b, the following day. Sample 2 was taken from a small hot stream that empties into Gardiner River about 60 rods upstream from the mouth of Hot River.

[c] Cold.

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TABLE 3.—*Radioactivity of waters in Yellowstone Park*—Continued.

Name of source.	Location.	Temperature.	Reaction, etc.	Activity.	
				$g \times 10^{-4}$ U.	$g \times 10^{-11}$ Ra.
		°C.			
LOWER GEYSER BASIN.					
A cold spring	4 miles north of Fountain hotel near roadside.			8.2	31
Lower spring	Terrace Springs	63	Slightly alkaline	5.3	20
Middle spring	do	40	do	2.4	9.1
Hygeia Spring	Near army post	53	do	Trace.	
Fountain Geyser [a]		88	do	None.	
Pool and spring	Near Clepsytra Geyser	85	do	16.3	62
White Sulphur Spring	Near Fountain Geyser	59	do	32.6	124
Firehole Lake		85	do	8.5	32
Mushroom Pool	Near Great Fountain Geyser.	75	do	10	38
Pool	East of road, Excelsior basin.	65		34.7	131
Excelsior Geyser	Excelsior basin	92	Slightly alkaline	Trace.	
UPPER GEYSER BASIN.					
Cauliflower Pool	Biscuit basin	61	Neutral	6.5	25
Firehole River	Near army post	19		Trace.	
Spring	Near Gem Geyser	64	Faintly acid	70.5	268
Bench Spring		86	do	6.4	24
Asta Spring	Hillside Springs	86	Faintly alkaline	8.45	32
Hot Spring	Near Solitary Spring	52		26.5	101
Old Faithful Geyser		88		None.	
Pool and spring	Near Economic Geyser	81	Neutral	23.9	91
Do	Near Model Geyser	82	Alkaline	6.1	23
Spring	Near Spouter	70	do	8.1	31
Handkerchief Pool	Emerald Group	82	Faintly alkaline	4.8	18
A mountainside spring	Niobe Creek	13	do	67.5	256
"Reservoir" Spring	Water supply for Old Faithful inn.	31	Neutral	11.2	42.5
A roadside spring	3 miles up Spring Creek.	10.5	do	14.9	56.5
SHOSHONE GEYSER BASIN.					
Three Crater Spring			Alkaline	5.9	22.5
A sulphur pool	Near Sulphur Spring		Acid	40.9	155
HEART LAKE GEYSER BASIN.					
Pool and spring	Near Rustic Geyser		Alkaline	19.1	72.5
"Orange" Pool and Spring.	Head of basin		Strongly acid	4.7	17.8
WEST THUMB, YELLOWSTONE LAKE.					
Pool and spring (A)	1 mile north of army post.		Alkaline	37.5	142
Pool and spring (B)	do		do	1.2	4.6
Yellowstone Lake	At boat pier			1.4	5.3
The cold spring	Fish hatchery			22.6	86
Pool	Near Paint Pots		Acid	16.8	64
YELLOWSTONE RIVER LOCALITIES.					
Yellowstone River	Camp Howard		Neutral	None.	
Pool and spring	Mud Geysers; south basin of activity.		Acid	15.1	57
Do	East of Mud Geyser		do	54.6	207
Chrome Spring	Sulphur Mountain	88	do	None.	
A hot spring	Foot of lower falls, canyon.			3.0	11.4
Forest Hill Springs	Canyon		Acid	6.35	24.2
A cold spring	Dunraven Pass, Mount Washburn.			10.3	39
Devil's Ink Pot	Mount Washburn		Acid	.6	2.3
Hellbroth Springs	do		do	1.35	5.2
Nymph Spring	Tower Falls		Neutral	6.9	26.3

[a] Sample was collected 5 minutes after the geyser played.

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RADIOACTIVITY OF WATER RESIDUES, SPRING DEPOSITS, AND ROCK SAMPLES.

The values given for the activities of solids in Tables 4, 5, and 6, represent the radium present per gram of the air-dry material. The quantity of material taken in each determination is recorded in the third column of the tables. The samples in Table 4 are water residues; those in Table 5 are incrustations deposited by the springs where the water issues. The samples were collected for the most part at the time the water samples were tested, and the radium was determined during the years 1906 and 1907. Several samples of travertine at Mammoth Hot Springs were collected by Capt. William H. Forsythe, U. S. Army. Some of the rock samples from typical formations in the park were obtained from the collection of the United States Geological Survey through the kindness of Dr. Arnold Hague.

TABLE 4.—*Radioactivity of water residues, Yellowstone Park.*

Name of source.	Locality.	Weight of sample (grams).	Radium per gram (gram × 10^{-12}).
Main Spring	Main terrace, Mammoth Hot Springs	4	4.33
New Blue Spring	do	4	5.4
Dedolph Spring	Highland terrace, Mammoth Hot Springs.	4.2	None.
Hot River	Mammoth Hot Springs	4	2.81
Giant Geyser	Upper Geyser Basin	2.5	None.

TABLE 5.—*Radioactivity of spring deposits, Yellowstone Park.*

MAMMOTH HOT SPRINGS.

Name of source.	Locality.	Weight of sample (grams).	Radium per gram (gram × 10^{-12}).
Hot River (1a)[a]		38	9.12
Hot River (2)[a]		100	8.28
Main Spring (1)	Main terrace	100	8.70
Main Spring (2)	do	54	11.2
Hymen Spring	Hymen terrace	38	4.3
Liberty Cap (a)		85	1.96
Liberty Cap (b)			1.36
Cleopatra Spring	Minerva terrace	59	15.24
Narrow Gauge Springs	Near the esplanade	58	4.26
Old Travertine	Hotel terrace	82	3.76
Do	Terrace Mountain	100	.08

NORRIS BASIN.

Locomotive		25	2.25
Congress Geyser		30	1.15
Opal Spring		30	.31
Primrose Spring		25	1.60
Paint Pot		30	2.39
Black Sulphur Spring		30	1.40
Orpiment Pool		30	.59
Paint Pot (Artists)	Gibbon Meadows	50	3.57

[a] Sample 1a is from main stream; No. 2 is from small outlet.

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TABLE 5.—*Radioactivity of spring deposits, Yellowstone Park*—Continued.

Name of source.	Locality.	Weight of sample (grams).	Radium per gram (gram × 10^{-12}).
LOWER GEYSER BASIN.			
Terrace Spring No. 2	Terrace Springs	25	1.87
White Sulphur Spring		25	.49
Pool and spring	Near Clepsytra Geyser	50	.11
Mud volcano	Near Rush Lake	50	6.4
Firehole Lake (1)		50	7.5
Firehole Lake (2)		40	6.9
UPPER GEYSER BASIN.			
Asta Spring	Hillside Springs	30	3.15
Bench Spring		30	1.06
Splendid Geyser		30	.08
Giant Geyser		25	.47
SHOSHONE GEYSER BASIN.			
"Sulphur" Spring		30	1.30
Wave Spring		30	0.46
HEART LAKE GEYSER BASIN.			
"Hillside" Spring	Near Rustic Geyser	30	1.41
"Orange" Spring	Head of basin	30	1.83
WEST THUMB, YELLOWSTONE LAKE.			
Paint Pot (a)		50	2.32
Paint Pot (b)		25	2.51
Fish Cone		50	0.21
YELLOWSTONE RIVER LOCALITIES.			
Mud Geyser		25	0.07
Devil's Ink Pot	Mount Washburn	73.4	0.34
Forest Springs	Yellowstone Canyon	25	1.45

TABLE 6.—*Radioactivity in rock samples, Yellowstone Park.*

Name of sample.	Locality.	Weight in grams.	Radium per gram (gram × 10^{-12}).
Rhyolite (a)	Golden Gate, Mammoth Hot Springs	25	1.51
Rhyolite (b)	do	25	1.7
Obsidian	Obsidian Cliff	50	2.32
Obsidian	Madison Plateau	25	1.57
Lava	Lava Creek	50	0.46
Petrified tree	Near Yanceys	70	0.065
Oolitic limestone	Near Mammoth Hot Springs	240	2.9
Rhyolite, specimen No. 504	Gibbon Canyon	55	2.84
Rhyolite, specimen No. 603	Hot Lake, Lower Geyser basin	56	3.24

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SUMMARY OF RADIOACTIVITIES.

To facilitate comparisons, most of the results presented in the foregoing tables are summarized in Table 7. The values are expressed in terms of the radium standard.

TABLE 7.—*Summary of radioactivities of gases, waters, and deposits in Yellowstone Park.*

Name of source.	Date of field test, 1906.	Radium per liter of gas (gram $\times 10^{-9}$).	Radium per liter of water (gram $\times 10^{-11}$).	Radium per gram of deposit (gram $\times 10^{-12}$).
MAMMOTH HOT SPRINGS.				
Main Spring	July 14	None.	None.	9.9
Blue Spring	July 15	None.	None.	.....
Cleopatra Spring	July 16	None.	None.	15.24
Hymen Spring	July 16	None.	Trace.	4.3
Bath Lake	July 17	Trace.	Trace.	.....
Orange Spring	July 18	Trace.	None.	.....
Hot River (1a)	July 16	.....	161	9.12
Hot River (2)	July 17	.....	111	8.28
Soda Springs	July 18	0.57	12.2	.....
Squirrel Springs	July 18	2.85	7.0	.....
NORRIS GEYSER BASIN.				
Congress Geyser	July 23	.....	4.4	1.15
"Black Sulphur" Spring	July 25	>15	17.4	1.4
Opal Spring	July 24	> 6.8	4.2	0.31
Locomotive	July 26	>19.8	.....	2.25
Primrose Spring	July 27	> 4.9	3.8	1.6
Orpiment Pool	July 28	25.7	.....	0.59
LOWER GEYSER BASIN.				
Terrace Spring (2)	Aug. 1	>4.9	9.1	1.87
Terrace Spring (1)	Aug. 1	>2.3	20	.....
Fountain Geyser	July 30	None.	None.	.....
Pool, Clepsytra Geyser	July 31	456	62	0.11
White Sulphur Spring	Aug. 1	44.5	138	0.49
Firehole Lake (1)	Aug. 3	329	32	7.5
Firehole Lake (2)	Aug. 3	182	.....	6.9
Mushroom Pool	Aug. 5	287	38	.....
Pool, Excelsior basin	Aug. 5	187	131	.....
UPPER GEYSER BASIN.				
Cauliflower Pool	Aug. 11	46.3	25	.....
Spring, Gem Geyser	Aug. 11	321	268	.....
Bench Spring	Aug. 11	139	24	1.06
Asta Spring	Aug. 12	.....	32	3.15
Splendid Geyser	Aug. 8	None.	.....	0.08
Giant Geyser	Aug. 9	None.	.....	0.47
Pool, Economic Geyser	Aug. 9	193	91	.....
Pool, Model Geyser	Aug. 7	462	23	.....
Old Faithful	Aug. 7	Present.	None.	.....
Handkerchief Pool	Aug. 10	158	18	.....
SHOSHONE GEYSER BASIN.				
Wave Spring	Aug. 13	>285	.....	0.46
Three Crater Spring	Aug. 13	328	22.5	.....
A sulphur spring	Aug. 14	340	155	1.30
HEART LAKE GEYSER BASIN.				
Hillside Pool, Rustic Geyser	Aug. 21	>266	72.5	1.42
Orange Pool	Aug. 22	92	17.8	1.83

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TABLE 7.—*Summary of radioactivities of gases, waters, and deposits in Yellowstone Park*—Continued.

WEST THUMB, YELLOWSTONE LAKE.

Name of source.	Date of field test, 1906.	Radium per liter of gas (gram×10^{-9}).	Radium per liter of water (gram×10^{-11}).	Radium per gram of deposit (gram ×10^{-12}).
Pool and spring (A)	Aug. 17	145	72.5	.....
Pool and spring (B)	Aug. 17	17	4.6	.....
Paint Pot	Aug. 19	>57	.....	2.32
Fish Cone	Aug. 18	47	.....	0.21
Yellowstone Lake	Aug. 17	101	5.3	.....
Pool near Paint Pot	Aug. 18	117	64	.....
YELLOWSTONE RIVER LOCALITIES.				
Pool, mud geysers	Aug. 25	18.6	57	0.07
Pool east of mud geysers	Aug. 26	59	107	.....
Forest Hill Springs	Aug. 28	.....	24.2	1.45
Devil's Ink Pot	Aug. 30	15	2.3	0.34
Nymph Spring, Tower Falls	Sept. 5	7.3	26.3	.....

DISCUSSION OF RESULTS.

GAS ACTIVITIES.

Thorium emanation.—The tabulated results show that marked differences exist in the activity of gases from different springs. In most cases the activity is due entirely to radium emanation. In at least 16 of the 82 gas sources examined thorium emanation was found associated with that of radium. These are the first springs on this Continent which to our knowledge have been found to contain thorium emanation, and the number reported in Europe is small. The initial activity due to thorium emanation varied from a mere trace to fifteen times that due to radium emanation in the same gas. Owing to the rapid rate of decay of the thorium emanation the results relative to it are only approximately quantitative and represent the minimum quantity. The thorium emanation was most marked at Norris Geyser basin and at Terrace Springs near the mouth of Gibbon River. Thorium emanation was not found alone in any gas. Some radium emanation always accompanied it. Actinium emanation was looked for, but without success. Its extremely rapid rate of decay (half value in four seconds) makes its detection difficult in small amounts under field conditions.

Relative activity.—In only one of the ten localities visited in the park were the escaping gases found, on the whole practically inactive. This locality is the well-known group of springs in the northern part of the park, known as Mammoth Hot Springs. Since the volume of the escaping gases from these highly carbonated waters is relatively large, this fact probably accounts for the extremely low concentration of the emanation in the gases and waters of this locality. In this connection it should be mentioned that the most active gas recorded (pool near Model Geyser, Upper Geyser basin) issued very

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A. OLD FAITHFUL GEYSER, UPPER GEYSER BASIN.

B. HOT SPRING, NORRIS GEYSER BASIN, WHERE THORIUM WAS FIRST DISCOVERED IN THE UNITED STATES.

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slowly, and that the next most active gas (pool near Clepsytra Geyser, Lower Geyser basin) required nearly an hour for the collection of a sample of 50 cubic centimeters in a bottle having a mouth 3 centimeters wide. The latter spring gives the appearance of discharging gas freely, but most of the bubbles proved to be steam.

Gases from European springs.—Some of the well-known thermal and cold springs on the European Continent are more or less charged with gases, like many of those of Yellowstone Park. The radioactive properties of the gases escaping from the European springs have been extensively studied by different investigators, and numerous quantitative results are thus available for comparison. The following table gives representative data for gases from springs in various European localities and for different localities in Yellowstone Park. The values for the activity in the third column of the table are expressed in electrostatic units.

TABLE 8.—*Radioactivity of gases from springs in Europe and in Yellowstone Park.*

Name of source.	Location.	Activity (electrostatic units, $I \times 10^3$).	Observer.
Grabenbäcker Quelle	Gastein	564	Mache.[a]
Elizabeth Stollen	do	412	Do.
Mühl Brunnen	Karlsbad	94.2	Mache and Meyer.[b]
Schloss Brunnen	do	50.2	Do.
Markt Brunnen	do	1.51	Do.
Wald Quelle	Marienbad	10.9	Do.
Ambrosius Brunnen	do	1.48	Do.
Urquelle	Teplitz-Schönau	21.9	Do.
Herrenbad Quelle	Fischau	2.18	Mache and Meyer.[c]
Haupt Quelle	do	2.60	Do.
Johannabad	Baden	16.6	Do.
Vauquelin	Plombières	184	Curie and Laborde.[d]
Bains des Dames	Luxeuil	23	Do.
Chomel	Vichy	18	Do.
Viktoria Brunnen	Oberlahnstein	1.25	Borne.[e]
Schützenhof Quelle	Wiesbaden	50	Henrich.[f]
Orpiment Pool	Norris basin	47	Schlundt and Moore.
Firehole	Lower Geyser basin	600	Do.
Spring and pool near Clepsytra Geyser	do	834	Do.
Bench Spring	Upper Geyser basin	254	Do.
Pool near Economic Geyser	do	353	Do.
Three Crater Spring	Shoshone Geyser basin	598	Do.
Fish Cone	West Thumb, Yellowstone Lake.	85	Do.
Nymph Spring	Tower Falls	13.3	Do.

[a] Sitzungsber. K. Akad. Wiss., Wien, Abt. 2a, vol. 113, p. 1329.
[b] Idem, vol. 114, p. 355.
[c] Idem, vol. 114, p. 545.
[d] Compt. Rend., vol. 138, p. 1150
[e] Jahrbuch Radioak., vol. 2, p. 77.
[f] Sitzungsber. K. Akad. Wiss., Wien, Abt. 2a, vol. 113, p. 1092.

Although the values for the activity as given by different observers are based upon somewhat different systems of reckoning (some investigators, Mache, for example, do not include the ionization effect of the disintegration products), still the values given show that the gases from the springs in Yellowstone Park are fully as active as those from European sources.

Helium not determined.—In several of the more active European springs it is known that helium is one of the constituents of the escaping gas. No tests were made by us to ascertain the presence of

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helium in any of the gases tested. The marked radioactive properties of the gases from many of the springs would make an examination of the gases for helium and the other rare gases very desirable.

ACTIVITY OF WATERS.

Inferences from different results.—The tabulated results clearly show that the thermal waters in different localities and even in the same locality differ considerably in activity. In some samples no activity was detected. Several cold springs were also tested. These likewise showed marked differences in activity, and their average somewhat exceeds that of the thermal springs. It is evident then that the temperature of the waters is independent of their activity. Similar variations in activity were found by Boltwood[a] in his extensive tests of the radioactive properties of the waters of Hot Springs, Ark., and by us in connection with the examination of some natural waters of Missouri.[b] The acidity or alkalinity of the water seems to have no connection with its activity.

Is the activity of the waters due to radium emanation which has diffused into them in the course of their underground flow, or is it produced by the radium that the waters carry in solution? As those water residues which were examined yielded only traces of radium emanation, we may conclude that the radium salts in solution are responsible for only a small part of the total activity, most of which is due to radioactive gases that have diffused into the waters.

Some of the differences observed in the activities are readily explained. The water of boiling springs and therefore of geysers almost invariably gave negative tests. Such a temperature is not favorable for the retention of dissolved gases. The escaping steam and the consequent agitation of the waters are both effective in removing any radioactive gases that may have been absorbed by the water.

The same effect may be caused in another way. If a large volume of gas is evolved from a spring, whose temperature may lie considerably below the boiling point, the emanation is swept out of the water by the gas. Such a condition also is not favorable for the accumulation of radioactive gases. In such a spring the activity of the gas also will prove to be low, although a considerable amount of emanation may have been removed by it. If these conditions were not considered such a spring might be classified as inactive, though its residue on evaporation might be found to contain appreciable quantities of radium. Most of the springs tested at Mammoth Hot Springs are examples of this condition. All of the springs on the Main Terrace gave negative results for both waters and gases, within the limits of error of our instruments under field conditions, and yet the residues and deposits, as Tables 4 and 5 show, greatly exceed in

[a] Am. Jour. Sci., vol. 20, 1905, p. 128.
[b] Trans. Am. Electrochem. Soc., vol. 8, 1905, p. 291.

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activity those of springs in other localities, the waters of which were found to be radioactive in a marked degree.

At all events the results for waters and gases show that the underlying rock in the park contains radium and in some localities thorium in sufficient quantities to make the waters and gases decidedly radioactive.

Comparison with European waters.—The radioactive properties of European thermal and mineral waters have been studied extensively by different investigators. From the numerous quantitative data a few have been selected and arranged in tabular form. Some of the values obtained by Boltwood in his examination of the waters of Hot Springs, Ark., are incorporated in the table, as well as values obtained for some Yellowstone Park waters.

TABLE 9.—*Radioactivity of spring waters in Europe and in the United States.*

Name of source.	Location.	Temperature.	Activity.		Observer.
			Electrostatic units ($l \times 10^3$).	Uranium (grams $\times 10^{-1}$).	
		°C.			
Grabenbäcker Quelle	Gastein	36.3	155		Mache.[a]
Elizabeth Stollen	do	46.8	133		Do.
Mühl Brunnen	Karlsbad	39.2	31.5		Mache and Meyer.[b]
Schloss Brunnen	do	30.2	17.4		Do.
Markt Brunnen	do	44.6	3.11		Do.
Wald Quelle	Marienbad	7.0	4.57		Do.
Ambrosius Brunnen	do	7.8	1.62		Do.
Urquelle	Teplitz-Schönau	45.9	4.96		Do.
Herrenbad Quelle	Fischau	18.5	0.56		Do.[c]
Haupt Quelle	do	23.3	0.71		Do.
Johannabad	Baden	30.0	4.54		Do.
Quelle am Schweizergang	St. Joachimsthal	14.2	185		Do.
Vauquelin	Plombières		9.4		Curie and Laborde.[d]
D'Alun	Aix-les-Bains		10.5		Do.
Chomel	Vichy		0.7		Do.
Viktoria Brunnen	Oberlahnstein				Borne.[e]
Hirten Brunnen	Odenwald, Hessen	10.3	12.5		Schmidt and Kurz.[f]
Kaiser Friedrich Quelle	Offenbach	19.5	1.1		Do.
Elizabeth Brunnen	Kreuznach	9.6	13.0		Do.
Rakoczy	Bad Kissingen		2.86		Jentzsch.[g]
Koch Brunnen	Wiesbaden		2.3		Henrich.[h]
Imperial Spring	Hot Springs, Ark	60.8		266	Boltwood.[i]
Twin Spring (north)	do	62.4		65.4	Do.
Arsenic Spring (north)	do	56.4		23.9	Do.
Liver Spring	do	8.0		17.4	Do.
Dripping Spring	do	57.8		7.7	Do.
Cave Spring	do	57.2		3.7	Do.
Sweet Springs	Sweet Springs, Mo	Cold.		23.7	Moore and Schlundt.[j]
Hot River	Mammoth Hot Springs.	51	26.3	37.9	Schlundt and Moore.
Apollinaris Spring	South of Mammoth Hot Springs.	9.2	22.1	31.9	Do.
Realgar Spring	Norris basin	Thermal.	7.4	10.6	Do.
Firehole Lake	Lower Geyser basin	85	5.9	8.5	Do.
Bench Spring	Upper Geyser basin	86	4.44	6.4	Do.
Pool and spring	Near Economic Geyser	81	16.6	23.9	Do.
Three Crater Spring	Shoshone basin		4.1	5.9	Do.
Nymph Spring	Tower Falls		4.8	6.9	Do.

[a] Sitzungsber. K. Akad. Wiss., Wien, Abt. 2a, vol. 113, p. 1329.
[b] Idem, vol. 114, p. 355.
[c] Idem, vol. 114, p. 545.
[d] Compt. Rend., vol. 142, 1906, p. 1462.
[e] Jahrbuch Radioak, vol. 2, p. 77.
[f] Phys. Zeitschr., vol. 7, 1906, p. 214.
[g] Idem, vol. 8, 1907, p. 887.
[h] Sitzungsber. K. Akad. Wiss., Wien, Abt. 2a, vol. 113, p. 1092.
[i] Am. Jour. Sci., vol. 20, 1905, p. 128.
[j] Trans. Am. Electrochem. Soc., vol. 8, p. 291.

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A comparison of the activities of the thermal waters of Yellowstone Park with those of European springs, as given by the foregoing table, shows that with a few exceptions the quantity of radium emanation carried is of the same order of magnitude and that marked variations exist. It is seen that the European springs in localities where deposits of pitchblende occur are distinctly more radioactive. In making comparisons of this kind, however, it must be borne in mind that the temperature of most of the park waters is near the boiling point, and that this factor is unfavorable for the accumulation of the emanation. It is worthy of note, in this connection, that the gases escaping from many of the springs in the park contain about the same quantity of radium emanation as the most active European thermal springs, which are located in regions where extensive deposits of radioactive minerals occur. It is therefore probable that many of the park waters traverse radium-bearing minerals in the course of their underground flow.

The waters of Hot Springs, Ark., are probably fully as active as those of the park, but their temperatures average considerably lower. The gases rising from two of the springs at Hot Springs were found by Boltwood [a] to be less active than equal volumes of gases separated from the waters by boiling, a result in direct contrast with our observations on the thermal springs of the park.

A discussion of the results in the foregoing table with respect to the hydrography of the different localities lies beyond the scope of this paper.

RADIUM CONTENT OF DEPOSITS AND ROCKS.

Comparative activity of different rocks.—At Mammoth Hot Springs the waters are calcareous, the dissolved material being derived from the underlying Jurassic and Cretaceous. At the other basins the waters are siliceous (some alkaline, some acid), the dissolved material being derived from the rhyolite of which the park plateau is largely formed. In both classes of deposits radium was detected.

The deposits of travertine at Mammoth Hot Springs contain radium in appreciable quantities. The activity of the residue obtained by evaporating the water is about half that of the deposits, showing that the radioactive material is largely deposited with the components that come out of solution first. This fact alone would account in a large measure for moderate differences in the radium content of the deposits formed by different springs of similar origin. The values obtained at Mammoth Hot Springs for the radium content of the deposits from the actively flowing springs, however, are of the same order of magnitude. The radium content of these deposits averages about 8×10^{-12} grams per gram of material, a value two and one-half times greater than the

[a] Am. Jour. Sci., vol. 20, 1905, p. 128.

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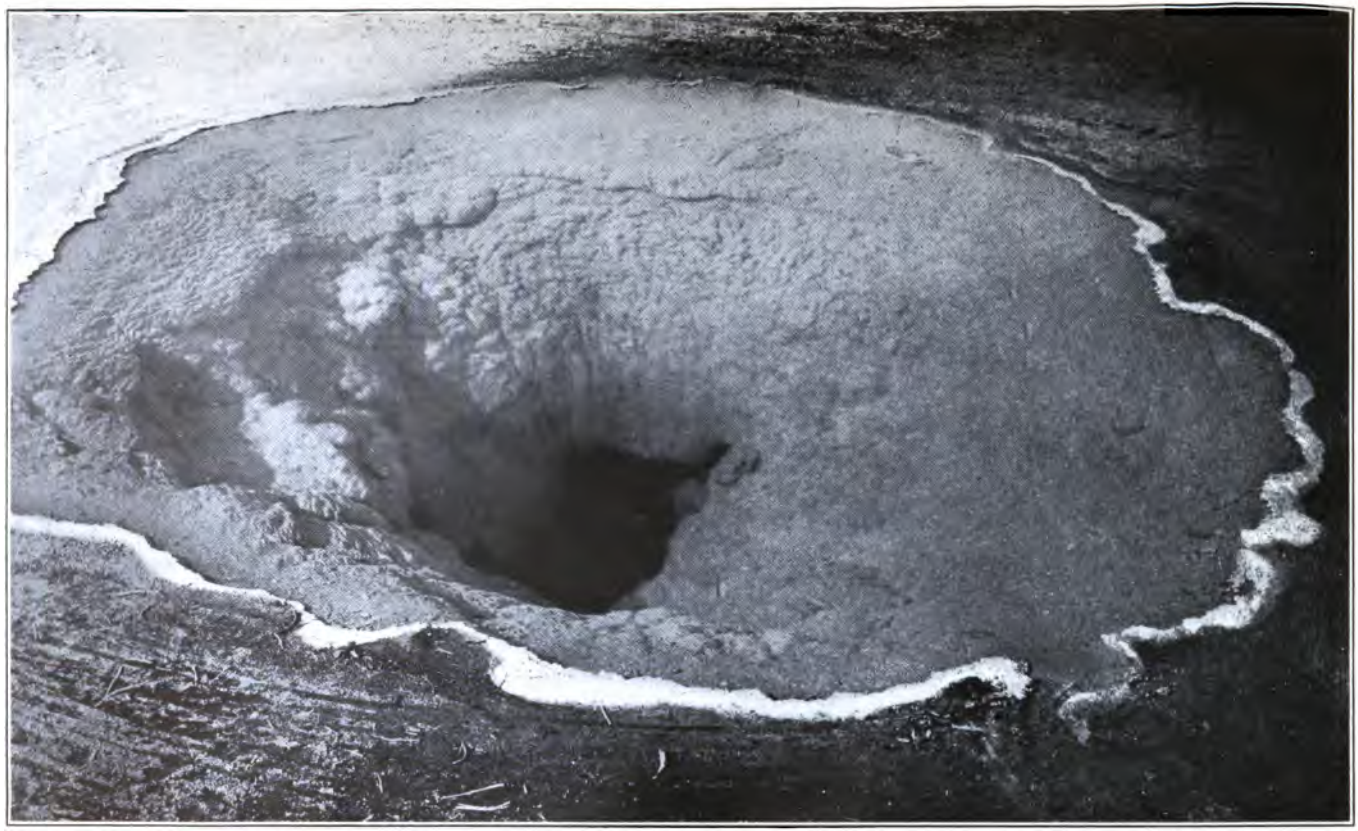

MORNING GLORY POOL, UPPER GEYSER BASIN.

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radium content of the rock from which the deposits are probably derived, and about five times the average radium content of the igneous rock of the park. To account for the concentration of radium in these spring deposits more experimental work is necessary. An investigation of the solvent action of hot, carbonated water on radium-bearing rock samples at different pressures might throw some light on the question. Again, the fact that radium in the Mammoth Hot Spring deposits is largely deposited with the components that first come out of solution may be connected with the numerous growths of algæ in these hot waters, which may act as precipitating reagents.

The siliceous deposits from some of the springs in the other basins of thermal activity likewise show a higher radium content than the igneous rock of the vicinity. In some cases the content is several times greater, but this result is not general. In fact, the nearly pure silica deposits from most of the geysers and the older springs contain less than half as much radium as the underlying rhyolite. The location of the springs appears to be related to the radium content of the residue. The residues with a radium content greater than that of adjoining rocks come, as a rule, from relatively new springs which are close to the outcropping rock. The disintegrated rock material from the so-called mud pots, paint pots, and mud volcanoes were also found to contain more radium than the park rhyolite.

Radioactive equilibrium.—Another question naturally arises in this connection: Is the radium thus deposited in radioactive equilibrium with its parent uranium? Some experimental evidence obtained indicates that far less uranium is deposited than the radium content requires. Of course, the quantity of uranium considered here is too small to be detected by chemical analysis, but if radium were present in the equilibrium ratio the activity of the deposits would remain practically constant for years. Now, the radium present in the old terraces, long since dry, is considerably below the average value for the recent deposits. A sample of travertine from Terrace Mountain, the scene of the first hot-spring activity at Mammoth Hot Springs, contains only about 1 per cent of the radium found in the present-day deposits of Jupiter terrace and Main terrace. Again, a sample of travertine from Hotel terrace, on which the government fort and buildings stand, carried only about 40 per cent of the radium found in most of the present-day deposits. Of course, these results might possibly be attributed to loss of radioactive material through weathering; but the hypothesis that radium and uranium are not deposited in radioactive equilibrium also furnishes a satisfactory explanation for the fact.

Estimate of age of deposits.—If we start with a given quantity of radium, separated from its parent uranium, at the end of 2,600 years,

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according to recent determinations, one-half of it would be transformed into inactive products, at the end of another such period there would be only one-fourth of the original amount, and so on. If we assume, then, that the uranium deposited with the radium is far below the equilibrium quantity, the experimental results obtained follow. Moreover, from the data thus in hand the approximate age of the old deposits can be calculated. The application of these data to the question of the age of the deposits of course involves the assumption that the original radium content of the travertine in the old terraces was approximately the same as in the new. Such an assumption is not far from the truth. The similarity of the waters of this locality as a whole in regard to their radioactive content, as well as in other respects, is very close and indicates a common origin. Moreover, some of the old terraces are well within the zone of present activity. The travertine of Terrace Mountain is overlain by glacial bowlders. Since its activity is only 1 per cent of that of the recent deposits, its age is about 20,000 years,[a] which would also be the approximate time that has elapsed since the glacial period in the park.

Comparative test for uranium by analysis.—Another line of experiments bearing on this question was suggested by some results obtained quite recently in determining the radium present in some of the "tufa" deposits made by the springs at Hot Springs, Ark. These deposits, like the travertine at Mammoth Hot Springs, are calcareous. The radium content[b] of one of these deposits indicated the presence of about one-half of 1 per cent of uranium, a quantity well within the range of analytical methods. Investigation of the question from this standpoint would be of interest. The deposit in question, which was obtained from the Palace Spring, is three times as active as the famous Bath Springs of England tested by Strutt.

RELATION TO HYDROTHERMAL ACTIVITY.

Assuming that the thermal activity in the park is due to recent extrusive lava flow, or intrusive lava masses, the question arises to what extent the radium content of these rocks affects their rate of cooling. To what extent is the radium responsible for the continued hydrothermal activity? We have attempted no calculations with the data obtained from the Yellowstone Park rocks, for we do not know the volume of water discharged by these springs, and so lack data for calculating the heat dissipated by the water. At Hot Springs, Ark., the present flow from the springs is given by Haywood and Weed[c] in their reports on the Hot Springs of Arkansas, at 850,000

[a] This would be 14,000 years if we accept 2,000 years as the half-time period of radium.

[b] Trans. Am. Electrochem. Soc., vol. 12, 1907, p. 247.

[c] Haywood, J. K., Report of an analysis of the waters of the hot springs on the Hot Springs Reservation, Ark.; and Weed, W. H., Geological sketch of the Hot Springs district: 57th Cong., 1st sess., S. Doc. No. 282 1902 pp. 31, 93.

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gallons daily. A simple calculation shows that the heat dissipated by the springs, flowing at the present rate during ten thousand years, would be furnished by approximately one cubic mile of solid lava cooling from its fusion point to the temperature of boiling water. Assuming that the radium present in the rocks is even somewhat greater than the average value found by Strutt[a] and by us, for igneous rocks (say 5×10^{-12} grams per gram of rock), the heat supplied by it per cubic mile of rock is about one-tenth of 1 per cent of the heat dissipated by the water.

The rock samples tested for radium gave values that average only a little more than Strutt's average for rhyolites and basalts—about 2×10^{-12} grams radium per gram of rock. These data certainly seem to indicate that the hydrothermal activity so manifest in the park is not connected with localized deposits of radium. In the above calculations the question of heat lost by diffusion and other factors is not taken into consideration, but after allowing a generous margin for error we do not see how more than 1 per cent of the heat required for the hydrothermal action can be ascribed to the radium content of the rock. It is true that a sample of limestone from Mammoth Hot Springs, which Arnold Hague considers typical of the underlying Mesozoic limestones, is more active than the most active of Strutt's sedimentary rocks,[b] a sample of oolite from the neighborhood of the Bath thermal springs of England, but this coincidence alone is not of sufficient importance to justify a verdict.

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[a] Proc. Roy. Soc., vol. 77, p. 472.

[b] Idem, vol. 78, p. 150.

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